MASSACHUSETTS INSTITUTE OF TECHNOLOGY

STUDIES OF HUMAN DYNAMIC SPACE ORIENTATION USING TECHNIQUES OF CONTROL THEORY

Principal Investigators: L. R. Young
Y. T. Li

December 1964

Second Semi-Annual Status Report on
NASA Grant NsG-577

UNPUBLISHED PRELIMINARY DATA

MAN-VEHICLE CONTROL LABORATORY
CENTER FOR SPACE RESEARCH
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139

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INTRODUCTION

The Man-Vehicle Control Laboratory has completed its first full year of research under the subject grant; this report presents a summary of the accomplishments during this period and our plans for the future. This report does not contain detailed results of experiments, for which the reader is referred to our technical reports and theses. Rather, it takes a broad look at the goals of our research in relation to the larger fields of control, aeronautics, astronautics, psychology and physiology, and measures our progress with respect to these goals, both as outlined in our proposal and modified by our experience.

This report summarizes the development of research equipment and methods, specific experimental and analytical results obtained using this equipment, and finally, preliminary experiments and plans for future research.

The block diagram of Figure 1 shows a general approach to the problem of transporting a vehicle from one place to another, and is drawn to illustrate the possible participation of man in any or all of the functions of guidance, control and stabilization. The choices of man or machine in each of these functions are extreme cases of the general situation of a greater or lesser degree of automatic assistance to the man or manual monitoring and override ability on a primarily automatic system. (This question is explored at length in the paper "The Roles of Men and Instruments in Control and Guidance Systems for Spacecraft," by C. S. Draper, H. P. Whitaker, and L. R. Young, presented at the 15th International Astronautics Federation, Warsaw, Poland, September 1964.)

The assignment of functions to men or automatic equipment should be made on a rational basis, considering the engineering characteristics of each design. Unfortunately, our knowledge of the engineering characteristics of men (or human operators as they are known in this context) is quite limited compared to our knowledge of the engineering characteristics of automatic guidance and control systems and flight vehicles. One approach is simulation of vehicle control under varying degrees of manual participation to test a proposed design. Simulation is certainly a necessity in the final design stage to check performance, and is also a useful preliminary design procedure. In the case of a completely automatic system, however, preliminary design is almost always done from calculations based on equations, specifications and models for the physical equipment. In an effort to achieve the same flexibility, economy, and potential system optimization for the design of manned systems, investigators have sought to develop models for the control characteristics of the human operator. Such models would permit much design to be carried out without simulation and would predict system performance and potential areas of difficulty in manned systems. Because of the great difficulties encountered in generating such models, (man is a non-linear, discrete, adaptive, time-varying, statistical controller with a "mind of his own"), the attention has been focused primarily on the case of single axis tracking of a time invariant plant with visual display and manual output control. As may be seen by the circled items in Figure 2, which is based on a block diagram in our research proposal, the "simple" case described above represents a small part of the multi-input, multi-loop control characteristics of the human operator in so restricted a task as orientation control.

Our goals, as outlined in our proposal, were to extend the control models of the human operator to include the description of the role of the non-visual motion sensors -- particularly the tactile and vestibular sensors -- in dynamic space orientation. These sensors are of vital interest, not only because of the deleterious effects of vertigo and the confusion that may exist when the visual and non-visual perceptions of orientation disagree, but because of the problem of vehicles in which the sensing of motion cues aids appreciably in the operator's control task. Our primary research this year has been devoted to investigation of the vestibular system control characteristics (semi-circular canals and otoliths) and the use of motion cues in closed loop control of simple stable and unstable systems. Less extensive research on nonlinear controllers and control models, postural control and adaptation to time-varying systems has also been started. The extent of this effort is indicated by the circled items of Figure 3.

Finally, our experience with manned systems has enabled us to broaden our view of the man-vehicle control problem and find some new areas of importance in which we have begun research towards extending control models and evaluating the capabilities and limitations of the human operator. Our modified view of the problem is shown in Figure 4. It is seen that these areas include the multi-axis, multi-loop problem, as well as the multi-input, and deal with some display and control aspects which show promise based on our understanding of the human operator.

DEVELOPMENT OF RESEARCH EQUIPMENT AND METHODS

A major expenditure of time and money during the first year of this research was on development of the experimental apparatus and data processing techniques necessary for performing the wide variety of experiments we plan. Summaries of this equipment are given below:

1.) Rotation simulator: To rotate subjects for stimulation of the semi-circular canals, and to tilt them with respect to the gravity vector in a precise controllable manner, we made use of the NE-2 two-axis simulator borrowed from NASA Ames Research Center. Installation and wiring of the equipment at M.I.T. was followed by extensive mechanical and electrical modification to make it a more accurate research tool.

2.) Linear acceleration cart: To stimulate the linear acceleration sensors without any rotation of the subject, we designed, constructed and tested a single-axis linear acceleration cart with a 32 ft. horizontal throw, maximum acceleration of 0.3 g's, threshold of 0.001 g's and nearly 1 cps bandwidth. This simulator was constructed on a very limited budget using second hand material. However, its potential has been successfully demonstrated in a number of experiments, and further modifications should increase its utility. (Ref. R. J. Schulte and R. E. Vreeland, "The Design and Construction of an

Acceleration Cart," (M.S. Thesis), MVC Lab Report T-64-1, June 1964).

3.) Stabilized motorbike: As a test vehicle in which visual and motion cues are used for dynamic orientation we have instrumented a motorbike. We measure tilt angle from the apparent vertical and steering deflection to identify the rider's control function, and are also developing automatic stabilization to attempt to duplicate the rider's performance.

4.) Posture Control Device: A simple apparatus has been designed and constructed to permit a subject to control a vehicle by a simple shift of his weight.

5.) Data reduction: Many of our experiments have required a digital computer for data reduction. We record data on FM analog tape, convert it to punched cards in the A/D converter of the GE-225 computer in the Electronic Systems Laboratory, and run the programs on the IBM 7094 of the Computation Center or the IBM 1620 of the Department of Aeronautics and Astronautics. Programs are being written to use the TX-0 computer to convert data directly to digital tape, and the installation of a time sharing console adjacent to our laboratory should facilitate the process.

6.) Analysis Programs: A SHARE program for spectral analysis and describing function calculation has been modified for our purposes, and programs have been written to determine phase plane switching lines associated with the human's non-linear control characteristics.

EXPERIMENTAL PROGRAMS

The experimental programs carried out in 1964 dealt with each of the parts of the general operator model -- sensor, compensation and output, and concentrated on both the "components" of the human and some of the system characteristics which make him such an interesting control mechanism. The major experimentation was at the sensory end, in our effort to complete control descriptions of the vestibular system -- semi-circular canals and otoliths. In control and compensation we concentrated on man's non-linear (switching) characteristics and his use of his control abilities with compatible and incompatible multiple inputs (visual and vestibular). At the output end we experimented with pulse and bang-bang controllers and the effects of sudden changes in control stick mechanical impedance. In closing the loop through the dynamics of the controlled vehicle, we performed experiments on the limits of control of unstable vehicles with and without motion cues. The inverted pendulum controlled element, programmed as a self pacing element, was used extensively as a scalar performance index. In addition, the motorbike equations of motion were studied with regard to required human equalization. A list of experiments performed is as follows:

1. Semi-circular canals as angular accelerometers
    a) Horizontal canal thresholds

b) Vertical canal thresholds

c) Eye movements

2. Otoliths as linear accelerometers

a) Thresholds in two body orientations

b) Frequency response

c) Eye movements

3. Eye stabilization as a multi-input control system

a) Head fixed, body moving - dark rotating environment

b) Head fixed, body moving - lighted rotating environment

c) Head fixed, body moving - lighted stationary environment

d) Head and body rotating - dark rotating environment

e) Head and body rotating - lighted rotating environment

f) Head and body rotating - lighted stationary environment

g) Head moving, body fixed - dark rotating environment

h) Head moving, body fixed - lighted rotating environment

i) Head moving, body fixed - lighted stationary environment

4. Closed loop control using vestibular sensors
    a) Pure rotation (Yaw), visual only
    b) Pure rotation (Yaw), motion only
    c) Pure rotation (Yaw), motion and visual indicator
    d) Pure linear motion
    e) Rotation with respect to gravity - darkness - hard chair
    f) Rotation with respect to gravity - darkness - soft chair
    g) Rotation with respect to gravity - motion and visual indicator
    h) Rotation with respect to gravity - motion and delayed visual indicator
5. Control of an unstable pendulous vehicle
    a) Visual display only
    b) Vestibular only (hooded cab)
    c) Vestibular and visual control (open cab)
6. Display configurations
    a) Non-linear
    b) Phase plane with optimum switching
7. Non-linear control characteristics of the human operator
    a) Switching line determinations with unstable systems
    b) Comparisons of continuous, bang-bang and pulse controllers

8. Control stick mechanical impedance

   a) Steady state tracking

   b) Sudden changes in impedance, importance of "local" feedback

PUBLICATION OF EXPERIMENTAL RESULTS

The results of items 1-5 will be published in a laboratory report in the spring of 1965, based on the forthcoming thesis of Mr. Jacob L. Meiry.

The results of item 5 will be presented at the IEEE International Convention in New York in March, and published in the IEEE International Convention Record under the title "Manual Control of an Unstable System with Visual and Motion Cues," by L. R. Young and J. L. Meiry.

Material relating to item 7 is contained in a manuscript entitled "Bang-Bang Aspects of Manual Control in High Order Systems" by L. R. Young and J. L. Meiry, submitted for the 1965 Joint Automatic Control Conference. Related data is in a B.S. thesis by P. S. Kilpatrick II, "Comparison of Relay and Linear Controllers for Systems with High Order Dynamics," M.I.T., June 1964.

The experiments on variable stick impedance (item 8) are contained in a B.S. thesis by I. Johnson, entitled "Human Response to Variations of Simulated Control Stick Forces".

Abstracts of these publications are appended to this report.

FUTURE DEVELOPMENT OF THE LABORATORY

Personnel:

The laboratory is fortunate in adding to its permanent staff Mr. Jacob L. Meiry, a research engineer with considerable military systems background who is completing his doctoral thesis in the laboratory.

Facilities:

Final architect's drawings have been completed for the new NASA-supported Center for Space Research to be constructed at M.I.T. The Man-Vehicle Control Laboratory has been assigned office and laboratory space including a moving base simulator area, and a computer room surrounded by four subject test rooms.

Submitted for
1965 Joint Automatic Control Conference

BANG-BANG ASPECTS OF MANUAL CONTROL IN HIGH ORDER SYSTEMS

by

Laurence R. Young* and Jacob L. Meiry**

Abstract

The tendency of many human operators to respond in a bang-bang fashion when controlling some high order systems is investigated. A three mode switch is compared with a linear control stick and shown to permit better manual control of systems with more lag than double integration. In experiments requiring stabilization of a moving base flight simulator programmed as an unstable system (undamped inverted pendulum) operators use the linear control stick in a bang-bang fashion. In place of quasi-linear models for these situations a simple on-off model for the human is suggested, and the switching lines and error trajectories in the phase plane are presented. The ability to control an unstable system with visual and motion cues is compared.

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Submitted November 12, 1964

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IEEE International Meeting
New York, March 1965

MANUAL CONTROL OF AN UNSTABLE SYSTEM WITH VISUAL AND MOTION CUES

by

Laurence R. Young and Jacob L. Meiry

Abstract

The effect of motion on a human operator's ability to control the orientation of an unstable vehicle was investigated. Stabilization of a simulated inverted pendulum was compared under conditions of only visual display, visual and motion cues, and only motion cues. The results are interpreted in terms of servoanalytic methods.

The XVth International Astronautical Congress
Warsaw, Poland - September 1964

THE ROLES OF MEN AND INSTRUMENTS IN CONTROL AND GUIDANCE SYSTEMS FOR SPACECRAFT

by

C. S. Draper, H. P. Whitaker, L. R. Young

Abstract

Control and guidance are functions that cause vehicles to move so that their assigned missions are successfully accomplished. Some aspects of these functions are primarily concerned with the collection, processing and use of intelligence and involve only signals representing information. For most of history these aspects have been performed by

human pilots. Until recent years, men also applied their muscles to transform the low power levels of nerve impulses to the much higher energies required to actuate the devices used for propulsion and maneuver in land, water and air vehicles.

Changes in the roles of human operators started when transportation developments introduced problems of control and guidance that were beyond direct solution by human abilities. Men continued to collect, process and apply information, but their senses had to be extended by instruments and their muscles needed to be supplemented by power-amplifying boosters. In addition, circumstances appeared in which automatic control and guidance had to be provided by inanimate systems because such craft as military missiles and drone aircraft do not carry men.

Astronautical craft for earth orbits and space exploration have been for the most part unmanned, but the immediate prospect of extended flights into space with human crews has stimulated very active comparison between the capabilities and limitations of men and inanimate devices for use in control and guidance systems.

In this paper the authors discuss the essential elements of control and guidance and review typical system configurations ranging from completely manual operation to arrangements with optional automatic action under the command of on-board and remote human monitors. The abilities of pilots to sense information, to carry out acts of skill, to evaluate data, to reach wise decisions, and to implement these decisions are considered from the standpoint of overall control and guidance performance. The conclusion reached is that the optimum system for extended space operations should be basically automatic and able to perform without help from remote equipment, but should also have provisions for on-board monitoring and optional operation by human pilots. For the purposes of information exchanges, the system should include provisions for radio and radar links with ground based installations.

The Apollo Spacecraft Guidance System, which will soon be used for manned exploration of the moon, is described as a practical mechanization of the principles which are discussed.

COMPARISON OF RELAY AND MANUAL CONTROLLERS FOR SYSTEMS WITH HIGH ORDER DYNAMICS

by

Philip S. Kilpatrick, II
Bachelor of Science Thesis
Massachusetts Institute of Technology
May 22, 1964

Abstract

This thesis compared a human operator's ability to control high order systems using linear and relay controllers.

The subject operated the control sticks to minimize the displayed error in a compensatory tracking problem. The disturbance or forcing function consisted of filtered white noise.

The controllers were compared by computing the average integral square of the error signal for tracking runs on different systems.

The results show the relay controller to be superior for a system with a transfer relation of $\frac{k}{p^2(p+1)}$. The results were not conclusive for the less difficult systems, $\frac{k}{p^2}$ and $\frac{k}{p^2(p/3+1)}$.

HUMAN RESPONSE TO VARIATIONS OF SIMULATED CONTROL STICK FORCES

by

Ivan S. C. Johnson, Jr.

Bachelor of Science Thesis
Massachusetts Institute of Technology
May 22, 1964

Abstract

A second order control stick system was designed and built. A d.c. reversible torque motor was used to provide the stick force. Efforts to achieve variability of dynamic force coefficients were hampered by the motor's delayed reaction to input current signals and need of a threshold current before producing any torque.

The magnitude of stick forces was changed without foreknowledge of the tracker in a pursuit problem. The induced error in tracking was taken as the measure of stick force importance for accurate tracking. Conclusions were that stick force is beneficial to the operator. Spring force information was found to be of most use. The magnitude of the error induced by stick force changes was independent of whether the force was decreased or increased. Largest disruption of tracking accuracy occurred when all force information was removed.

Possible reasons for the apparent minimization of force information importance at low frequencies were presented. The suggestion that the natural damping of the stick system is a critical variable was also forwarded.

THE DESIGN AND CONSTRUCTION OF AN ACCELERATION CART

by

Richard J. Schulte, 1st Lt., USAF
Russell E. Vreeland, Jr., Capt., USAF

Master of Science Thesis
Massachusetts Institute of Technology
June 1964

Abstract

This thesis presents a discussion of the problems encountered in designing and constructing a simulator to determine human vestibular response to a range of linear accelerations from 0-.3g's. Starting with a set of initial performance specifications, the designers have combined an array of commercially available components into a system, which, although requiring further refinements before completion, shows considerable promise of fulfilling the initial requirements.

The resulting system consists of a wheeled vehicle, driven by a cable and drum arrangement, powered by a hydraulic pump and motor, and controlled by a hydraulic-electric servo valve. Technical design considerations are presented along with a discussion of the "trade-offs" between various component options. A description of the system characteristics as well as an analysis of preliminary test results and recommendations for future system improvements are included.

HUMAN PERFORMANCE DURING A SIMULATED APOLLO MID-COURSE NAVIGATION SIGHTING

by

Charles M. Duke, Jr., Capt., USAF
Michael S. Jones, Capt., USAF

Master of Science Thesis
Massachusetts Institute of Technology
June 1964

Abstract

This is an investigation into the effects of certain variables on the performance of man doing a precise superposition task. This simulates the task that the project Apollo navigator will be required to perform during the mid-course (translunar and transearth) phases of the proposed lunar excursion. For this investigation, the Apollo sextant simulator located at the M.I.T. Instrumentation Laboratory, Cambridge, Massachusetts, was used. The variables were (1) rate of spacecraft motion, (2) magnification of sextant telescope, (3) orientation of landmark, and (4) star-landmark contrast ratio. In order to determine the effect of each variable individually, only one was varied at a time.

Three subjects were used. Each performed the superposition task by using a set of hand controllers until the star was on top of the landmark, as seen through the sextant telescope. At this point the subject pressed a "MARK" button, which recorded the error that he made in seconds of arc. For each given set of conditions, the subject performed the task 25 to 30 times. For each such series, the mean error was computed (absolute mean distance from perfect super-position.) Statistical tests were then applied to these means to check for significant changes in error due to changing one of the variables.

Results indicate that two of the four variables investigated have a statistically significant effect on the accuracy. The errors increase with faster craft motion, and at the higher rates more fuel must be expended to keep the landmark in the sextant's field of view. A greater magnification results in overall smaller errors, but more investigation should be done to determine if they are enough smaller to warrant heavy or more expensive equipment. Orientation of the landmark seemingly has no effect on the accuracy of the superposition task. However, orientation may have an

effect on landmark recognition, and this should be kept in mind during navigator training. The contrasts studied indicate that so long as both star and landmark are lighted sufficiently to be recognizable the errors will be essentially the same at any overall brightness level, with one exception. The exception is that a very bright star on a dim background seemingly increases the error. More studies should be made in this area to determine a maximum star brightness for acceptable error.

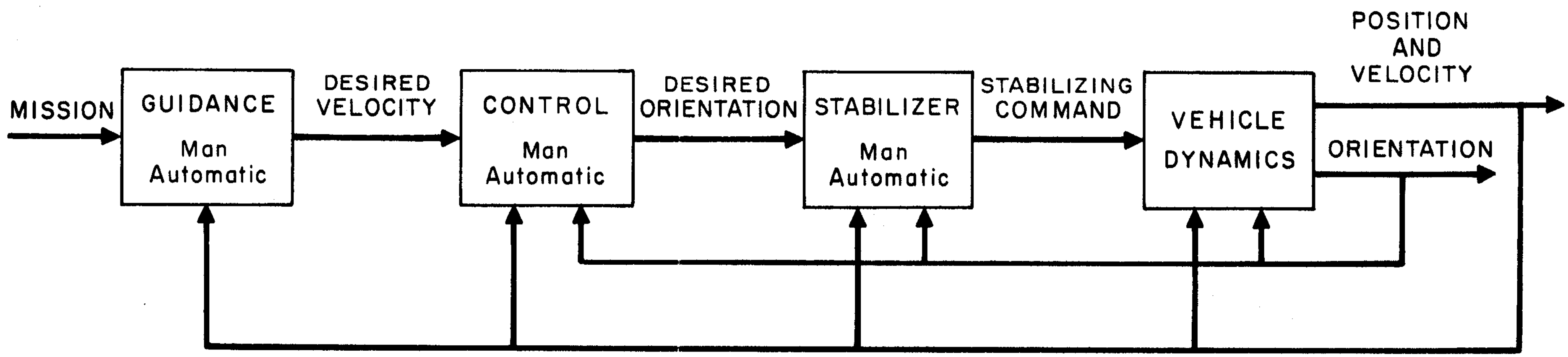

Fig. 1 Guidance, Control and Stabilization of a Vehicle.

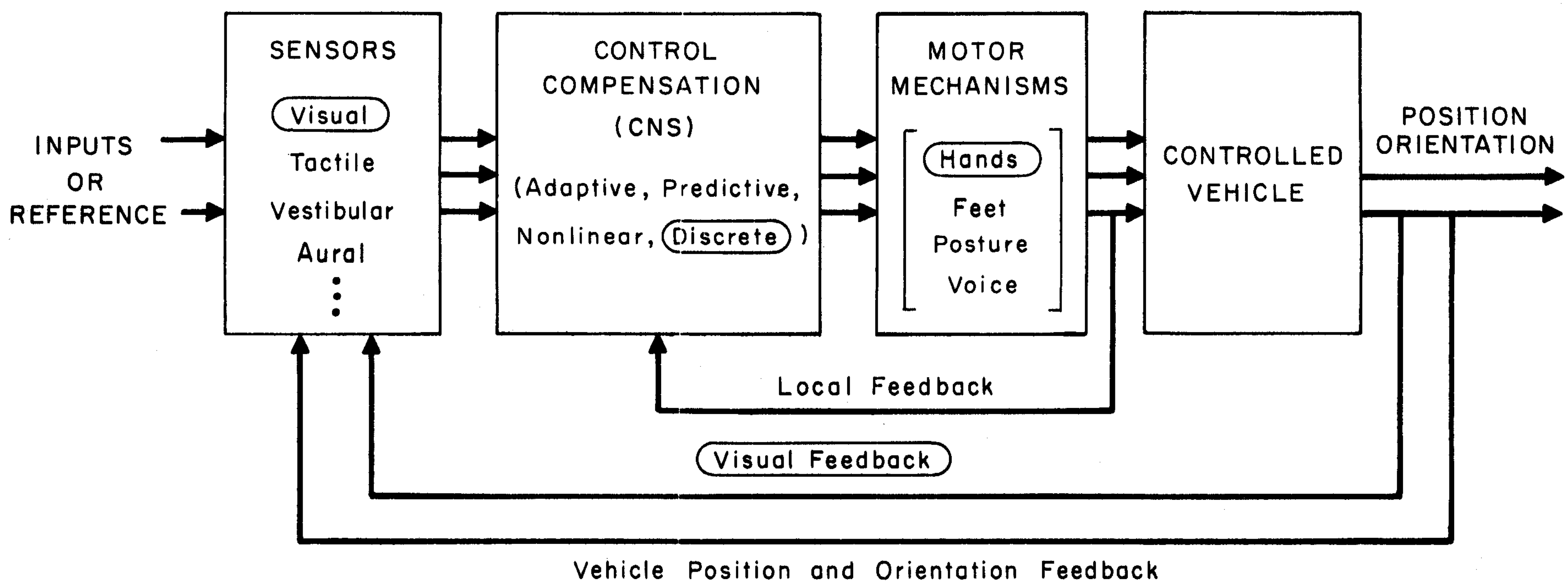

Fig. 2 General Block Diagram of the Man-Vehicle Control Problem
Circles Represent Major Areas Already Studied Thoroughly.

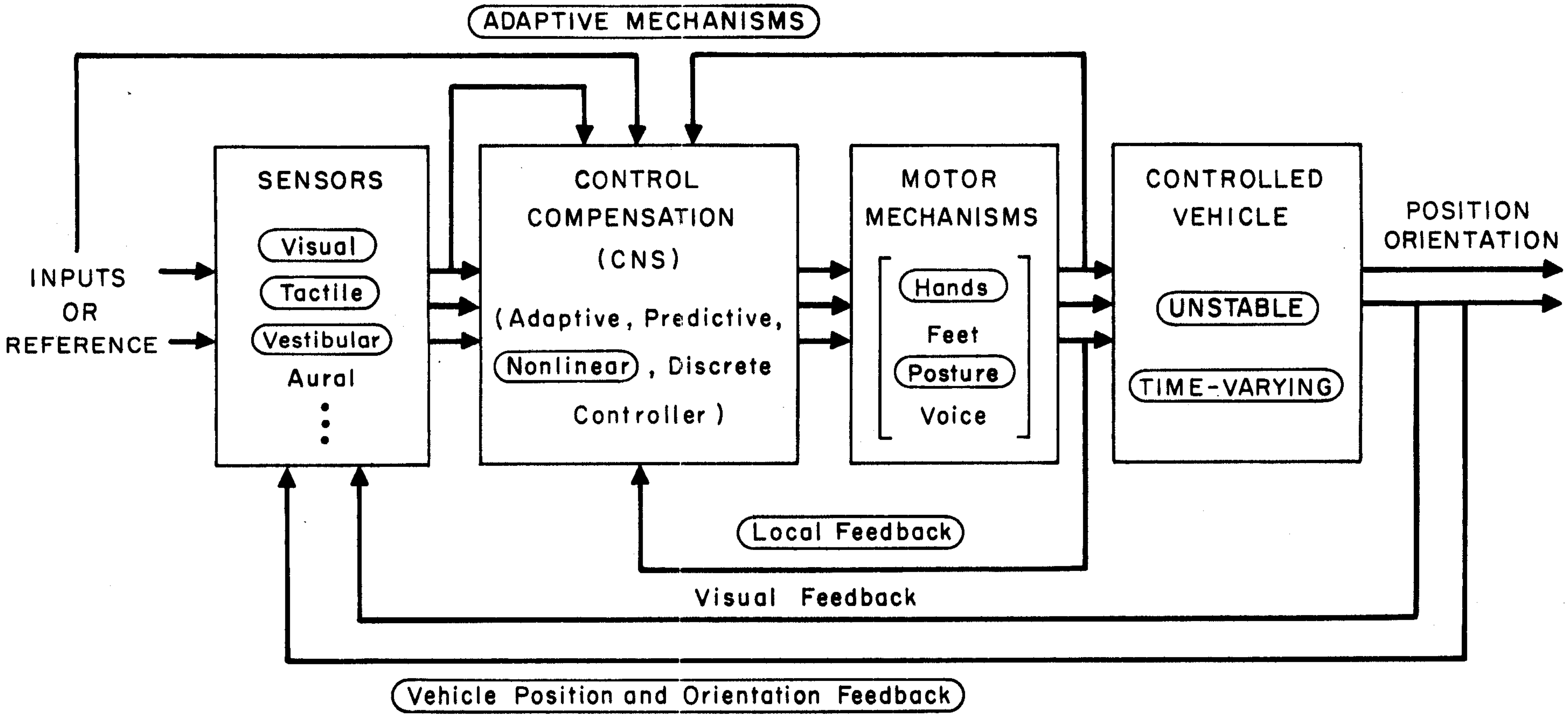

Fig. 3 General Block Diagram of the Man-Vehicle Control Problem
Circles Represent Major Areas Under Research at M.I.T.

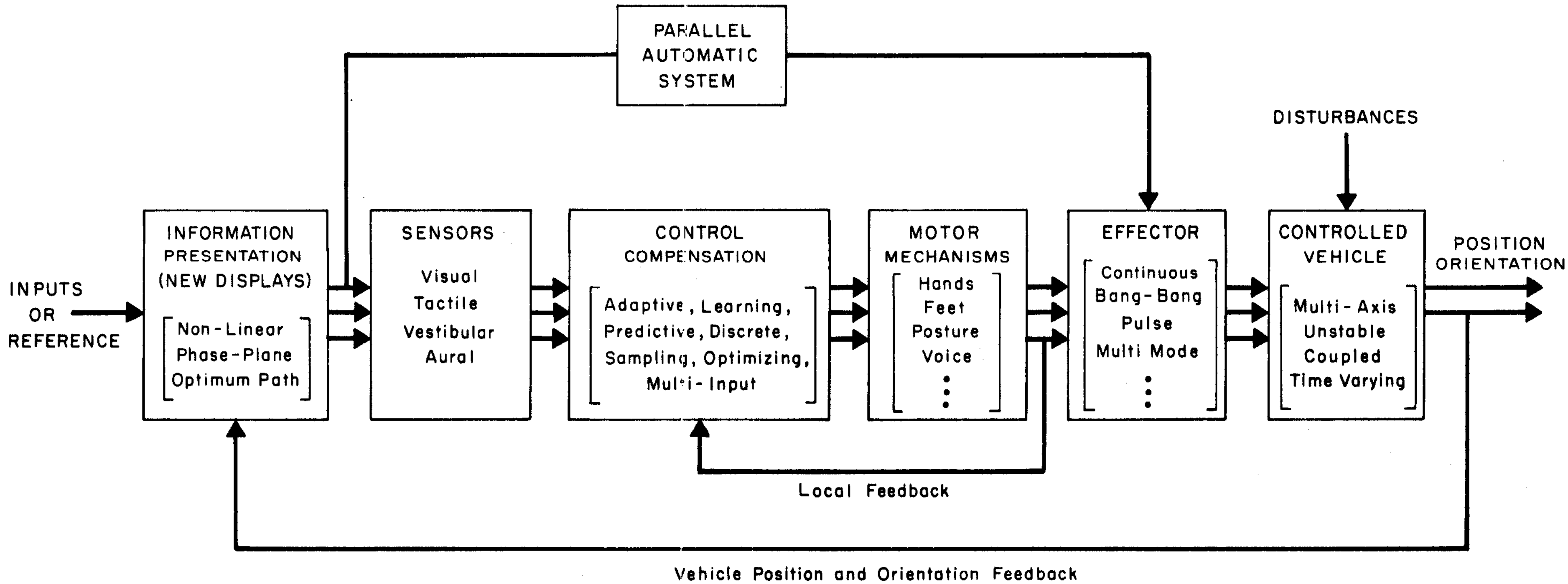

Fig. 4. Modified General Block Diagram of the Man-Vehicle Control Problem Showing some Newer Areas of Interest.